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Diode-Pumped Thulium (Tm)/Holmium (Ho) Composite Fiber 2.1- μm Laser

by G Alex Newburgh and Krysta Boccuzzi

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT We demonstrate the world's first composite fiber laser of holmium-core and thulium-doped cladding. The composite fiber was optically pumped by an 803-nm fiber coupled diode source and was demonstrated to emit at 2020 nm with 29% slope efficiency and at 2070 nm at 4% optical-to-optical with a peak power of 1.5 W.					
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Contents

List of Figures	iv
1. Introduction	1
2. Principle of Laser Operation	1
3. Optical Pumping of the Ho Core by Tm-modal Analysis	2
4. Fiber Spectroscopy	4
5. Experiment	7
6. Conclusion	9
7. References	10
List of Symbols, Abbreviations, and Acronyms	11
Distribution List	12

List of Figures

Fig. 1	Illustration of the Tm/Ho composite fiber laser principle	2
Fig. 2	Model of the RIP of the waveguide	3
Fig. 3	Plot of the first 2 modes supported by the waveguide	3
Fig. 4	Plot of the distribution of TE mode power in the core region, odd modes in red and even modes in blue	4
Fig. 5	(Left) The ground state absorption (GSA) ($^3H_6-^3F_4$) and stimulated emission (SE) ($^3F_4-^3H_6$) cross sections of the Tm silicate. (Right) The GSA ($^5I_8-^5I_7$) and SE ($^5I_7-^5I_8$) cross sections of the Ho silicate.	5
Fig. 6	(Left) The gain cross section of the (left) Tm silicate and (right) Ho silicate	6
Fig. 7	The effective gain cross section of the Tm silicate assuming a Ho core with 5% mode overlap with the Tm lasing modes. Shown in green is the gain cross section of Tm without the absorption of the Ho core.	7
Fig. 8	Schematic of the 800-nm diode pumped Tm/Ho composite fiber laser	7
Fig. 9	(Top) Schematic of the 800-nm diode-pumped Tm/Ho composite fiber laser with outcoupler. (Left) Q-CW laser performance of the Tm/Ho composite fiber indicating an overall conversion slope efficiency of 800-nm radiation to 2 micron radiation of 29%. (Right) Spectral output of the laser showing the presence of 1950-nm radiation attributed to leakage of Tm lasing through outcoupler.	8
Fig. 10	Laser performance of the 300-mm-long Tm/Ho composite fiber for various output coupler reflectivities.....	9

1. Introduction

Until now, laser sources have yet to be demonstrated that both emit in the atmospheric transmission window (2.1–2.5 μm) with excellent beam quality and with greater than 140 W of output power. Recently a 2.106- μm fiber laser was demonstrated to operate with near diffraction limited beam quality,¹ but was of low power (27 W), requiring a thulium (Tm) fiber laser to subsequently pump a holmium (Ho) fiber laser in order to produce the 2.1- μm radiation. While a high-power (300 W) single mode large mode area (Tm) fiber laser has been demonstrated,² the output wavelength fell short at 2040 nm. In order to address the need for a laser emitting at 2.1 μm with excellent beam quality and high power (>250 W) while possessing a simplified laser architecture, we have recently developed and begun testing a laser gain fiber architecture, the Tm/Ho composite gain fiber, now under US patent.³ The composite fiber architecture combines the functionality of the Tm fiber laser for production of the 1.9- μm radiation required to pump the rare earth ion, Ho-doped fiber laser into 1 fiber.

2. Principle of Laser Operation

The principles of operation of the composite fiber laser are sketched in Fig. 1. The output of an 808-nm diode-pumped laser (commercial electrical-to-optical [E-O] efficiency >50%) is focused into the 2 rare earth doped composite glass fibers of undoped clad ($\sim \varnothing$ 200 μm), Tm-doped clad ($\sim \varnothing$ 75 μm), and Ho-doped core ($\sim \varnothing$ 23 μm). Through the 2-for-1 process, a single 808-nm diode light photon is absorbed by the Tm ion ($^3\text{H}_6 \rightarrow ^3\text{H}_4$), which subsequently through a cross relaxation process produces an average of 1.5–1.8 photons in the $^3\text{F}_4$ level. The Tm ion residing in an inverted state may now transition ($^3\text{F}_4 \rightarrow ^3\text{H}_6$, 1.9 μm) to the ground state either through fluorescence or stimulated emission.

As drawn in Fig. 1, the fiber is capped on the left by a dichroic mirror, which allows passage of 800-nm light while reflecting wavelengths in the range of 1800–2200 nm (anti-reflective [AR] at 780–820 nm, highly reflective [HR] from 1800–2200 nm). On the right side, a dichroic mirror is optically coated to be HR for the wavelength range of 1800–2200 nm but partially reflective (PR) at 2000–2100 nm. A simple laser cavity is thus formed with the composite Tm/Ho composite fiber as its gain medium. The Tm portion of the fiber begins to produce 1900-nm light through laser oscillation.

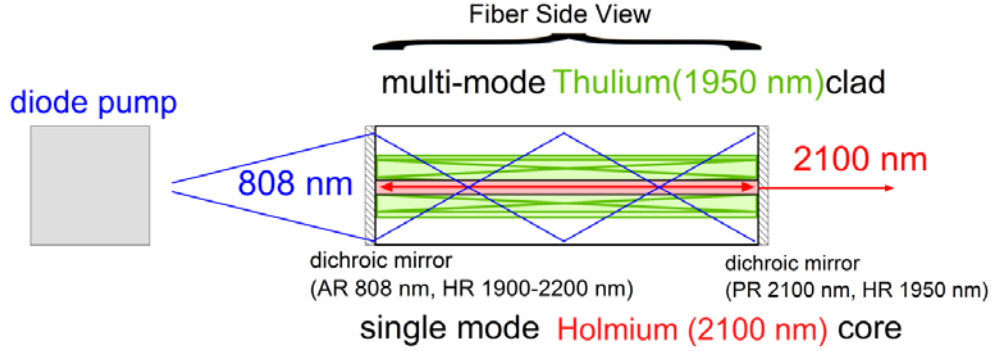


Fig. 1 Illustration of the Tm/Ho composite fiber laser principle

3. Optical Pumping of the Ho Core by Tm-modal Analysis

The large diameter with respect to the optical wavelengths of the Tm cladding ensures that the optical fiber lases with many optical modes. It is to be expected that a portion of the Tm laser power will overlap with the Ho core. This expectation is depicted in Fig. 1 through the crisscrossing green lines representing the bouncing of 1900-nm radiation as it circulates within the laser cavity. While this model is intuitively reasonable, a proper quantitative verification of this expectation was made as follows. The cylindrical fiber was collapsed to a 1-dimensional (1-D) profile, which allowed for an exact calculation of the finite number of optical modes supported by a waveguide of a given refractive index profile. The model of the planar dielectric waveguide was configured to the dimensions of the fiber and the numerical aperture (NA) of the core and clad. The electric-field distribution of the transverse electric (TE) modes was calculated through matching of sin and cosine functions and exponentially decaying function at the interfaces between regions of different refractive indices and an automated search for the propagation constants satisfying the boundary conditions using a program that I wrote in Matchcad.

The model duplicated the dimensions (23-, 75-, and 180- μm diameter) and NA of the core (0.01) and clad (0.12) of the composite fiber used in the experiment through a refractive index profile (RIP), as shown in Fig. 2

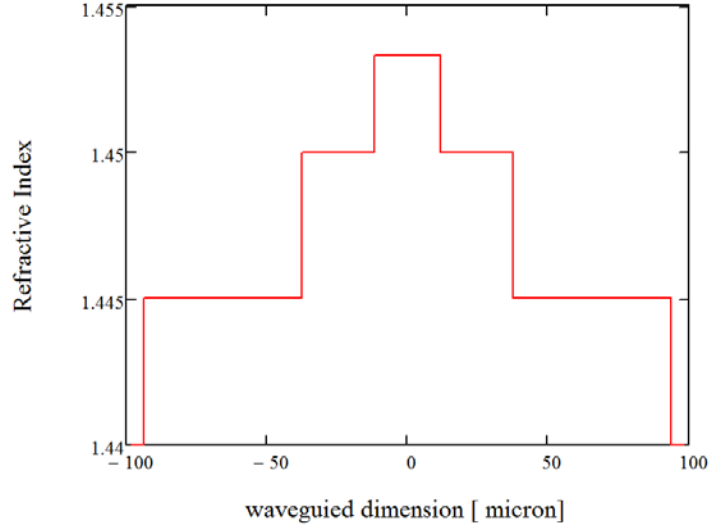


Fig. 2 Model of the RIP of the waveguide

It was found that the waveguide supported 13 odd and 13 even TE modes in the 2 clad and core waveguide. However, of the set of 26, only 4 odd and 5 even modes were exclusive to the core and first cladding. As the Tm laser modes are excluded from lasing in the second (undoped) cladding mode, our analysis of the overlap on Tm mode with core was restricted to the 9 modes only. Examples of the 2 lowest order modes intensity profiles and their placement within the waveguide are shown in Fig. 3. Note that a TE_0 order was not found by the program (a Gaussian-like mode was only found by reducing the NA of the core and/or narrowing the first clad layer).

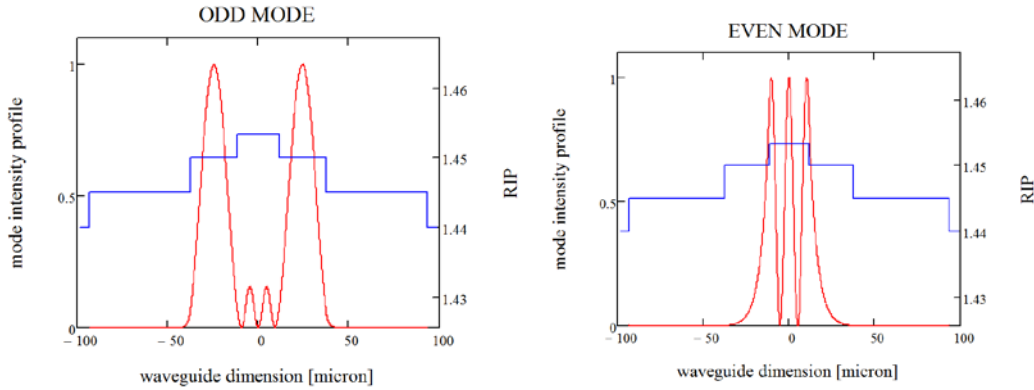


Fig. 3 Plot of the first 2 modes supported by the waveguide

In order to get an estimate the fraction of the power of the Tm laser power that overlapped with the Ho core, I calculated the sum of the 9 TE modes intensity that resided exclusively in the core region. A plot of the fraction of TE power in the core region is plotted in Fig. 4. Note that the representative fraction of power lies around

20% (exact calculation shows 21%). This result was somewhat unexpected as the ratio of the core to clad of the calculation was found to be

$$Ratio = \frac{w_{core}}{w_{core} + 2w_{clad}} = \frac{23}{75} = 0.3 \quad (1)$$

The discrepancy indicates that a high refractive index core “repels” the TE mode from the core region. Further investigations of mode model confirmed that as the refractive index of the core approached that of the first clad, the fraction of power residing at the core center was in agreement with Eq 1. *Thus, for the case of a 2-dimensional waveguide, the fraction of the power of the cladding modes overlapping that of the core would be the ratio of the core-to-cladding area in the limit that the core refractive index was equal to that of the cladding:*

$$Ratio = \frac{r_{core}^2}{r_{clad}^2} \quad (2)$$

where r_{core} and r_{clad} are the radii of the core and cladding layers, respectively.

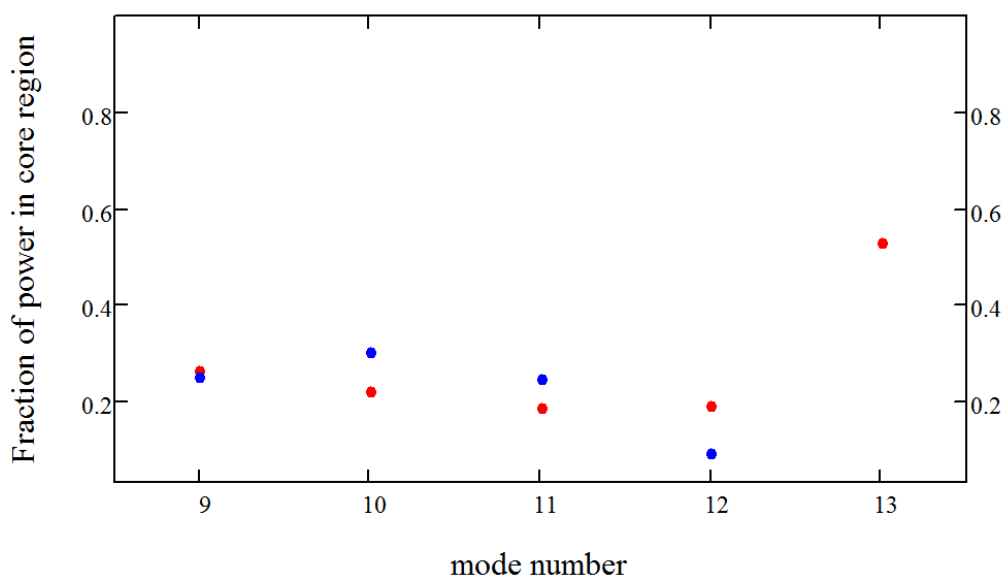


Fig. 4 Plot of the distribution of TE mode power in the core region, odd modes in red and even modes in blue

4. Fiber Spectroscopy

In order to properly prepare a fiber laser design using the Tm/Ho composite fiber, an accurate measurement of the absorption and emission spectroscopy of the 2 rare earth components in silicate glass, as produced by Advalue Photonics, was needed. Unlike commercial vendors of glass fiber where the fiber preform is often unavailable for absorption measurements, Advalue as partner in this endeavor

provided the US Army Research Laboratory (ARL) with polished samples of 1 wt % of Ho-doped and 4 wt % of Tm-doped glass.

Shown in Fig. 5 are the results displaying both the absorption cross sections of Tm and Ho silicate as well as the emission cross section derived from fluorescence measurements of the glasses using the Füchtbauer–Ladenburg method. Clearly, Tm emits most strongly around 1900 nm and Ho at 2050 nm. Fluorescence lifetimes of the 3F_4 and 5I_7 levels in Tm and Ho, respectively, were measured and found to be 1.3 and 3.7 ms.

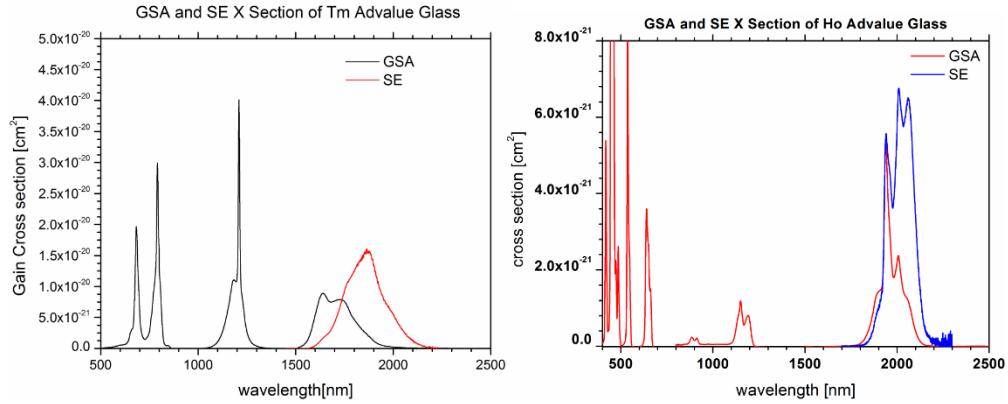


Fig. 5 (Left) The ground state absorption (GSA) (3H_6 - 3F_4) and stimulated emission (SE) (3F_4 - 3H_6) cross sections of the Tm silicate. (Right) The GSA (5I_8 - 5I_7) and SE (5I_7 - 5I_8) cross sections of the Ho silicate.

Armed with the spectroscopy of Fig. 5, we were now able to calculate the gain cross section, σ_g , of the Tm and Ho components of the fiber. Those results are shown in Fig. 6 for various inversion levels, $\beta = N_2/(N_1 + N_2)$ of the ions, where N_1 and N_2 are the ion densities of the ground and excited states, respectively; and $\sigma_g = \beta\sigma_{SE} - (1-\beta)\sigma_{SE}$, and σ_g , σ_{GSA} and σ_{SE} are the gain, ground state, and SE cross sections of the ion.

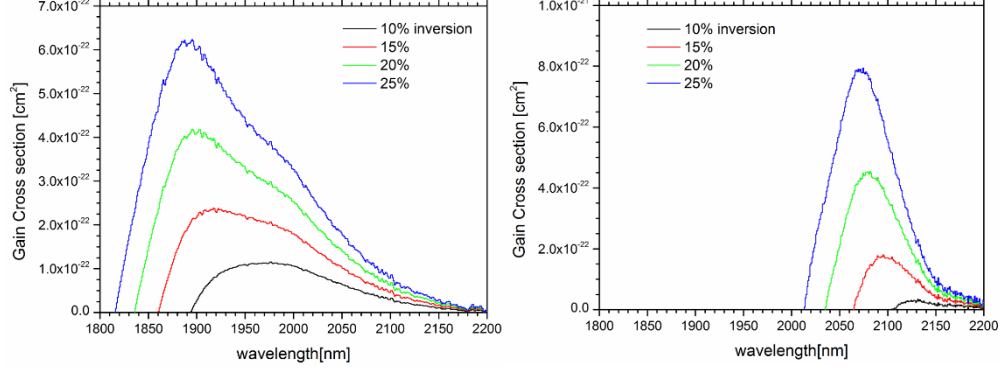


Fig. 6 (Left) The gain cross section of the (left) Tm silicate and (right) Ho silicate

In what will become apparent in the experiment portion of this report, the emission wavelength of the Tm/Ho composite fiber tended to arrange itself into wavelength bands. This was at first puzzling, but upon further reflection could be explained by the effective composite spectroscopy of the composite fiber. Recall that as the Tm portion of the fiber lases, a portion of its radiation is absorbed by the Ho core. From the perspective of Tm, the Ho core represents an additional loss. This loss can be modeled as an absorption of $\sigma_{\text{loss}}(\lambda) = \sigma_{\text{Ho-GSA}}(\lambda) * \frac{r_{\text{core}}^2}{r_{\text{clad}}^2}$. Incorporating this additional loss to the gain cross section expression for Tm, results in an expression of the effective gain cross of Tm,

$$\sigma_{g-\text{effective}} = \beta\sigma_{SE} - (1 - \beta)\sigma_{GSA} - \sigma_{\text{Ho-GSA}}\left(\frac{r_{\text{core}}}{r_{\text{clad}}}\right)^2 \quad (3)$$

The application of Eq. 3 with the assumption that the Ho core overlaps the Tm lasing modes by 5% yields the following gain cross section for the Tm portion of the composite fiber.

Figure 7 predicts that upon lasing, the Tm portion of the composite fiber will tend to emit only in the 1900-, 1980-, 2030-, and (possibly) 2130-nm bands.

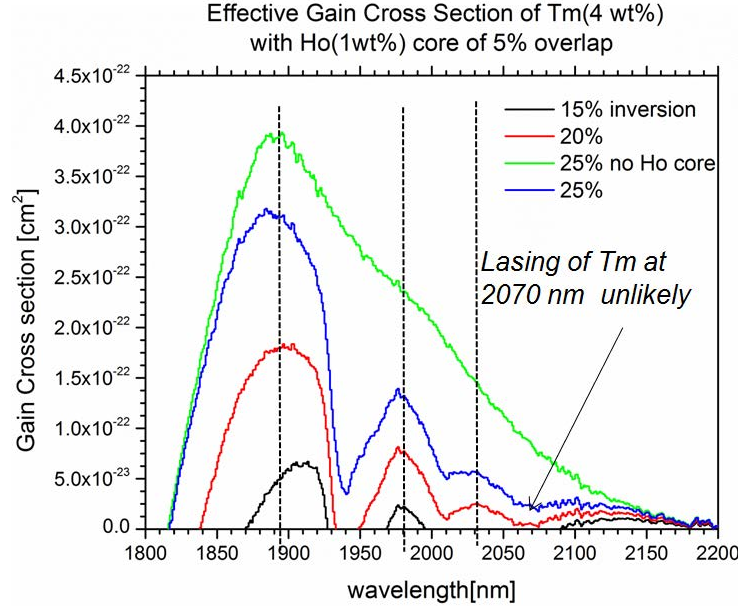


Fig. 7 The effective gain cross section of the Tm silicate assuming a Ho core with 5% mode overlap with the Tm lasing modes. Shown in green is the gain cross section of Tm without the absorption of the Ho core.

5. Experiment

To start, I designed and then obtained from Advalue Photonics of Tucson, Arizona, the world's first version of the composite optical gain medium fiber: Ho core (1 wt %)/Tm(4 wt %)/unclad glass fiber of 23/75 and 187 μm diameter, respectively. The entire fiber was clad by an additional glass layer of a diameter of 230 μm such that the fiber would have an NA angle of 0.57. The Ho core was nearly single mode in its waveguiding characteristics.

Initial experimentation began with the lasing of a 160-mm-long fiber of cleaved end and butt-coupled to a dichroic mirror as shown in Fig. 8. The dichroic mirror was coated to pass about 90% of the 800-nm fiber coupled diode laser radiation (fiber NA of 0.2, diameter of 400 μm) and reflect nearly 100% of 1800–2200 nm light. The cleaved end provided a PR of about 4% due to Fresnel reflection.

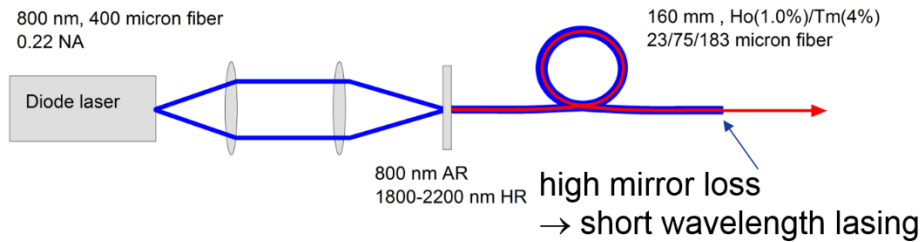


Fig. 8 Schematic of the 800-nm diode pumped Tm/Ho composite fiber laser

Under quasi-continuous wave (Q-CW) pumping conditions of 1-ms duration and a 10-Hz pulse repetition frequency (PRF), the Tm clad was shown to lase with a 40% optical-to-optical slope efficiency with emission at 1900 ± 5 nm with nearly 30-W peak power. This result implied that enough 1900-nm radiation would be available for the optical pumping of the Ho core. This expectation was tested in the next phase of experimentation when an output coupler designed for HR at 1900 nm and PR at 2050 nm was placed in contact (butt-coupled) to the end of the fiber as shown in Fig. 9. In this early set of trials, it was found that the composite fiber could be induced to lase at 2020 and 2040 nm. This was ascribed to the presence of the Ho core. Leakage of light through the outcoupler, as shown in Fig. 9 (right), indicates that the Tm-doped clad was induced to lase at 1950 nm. A total optical-to-optical slope efficiency of 29% was measured with peak powers of 2.5 W.

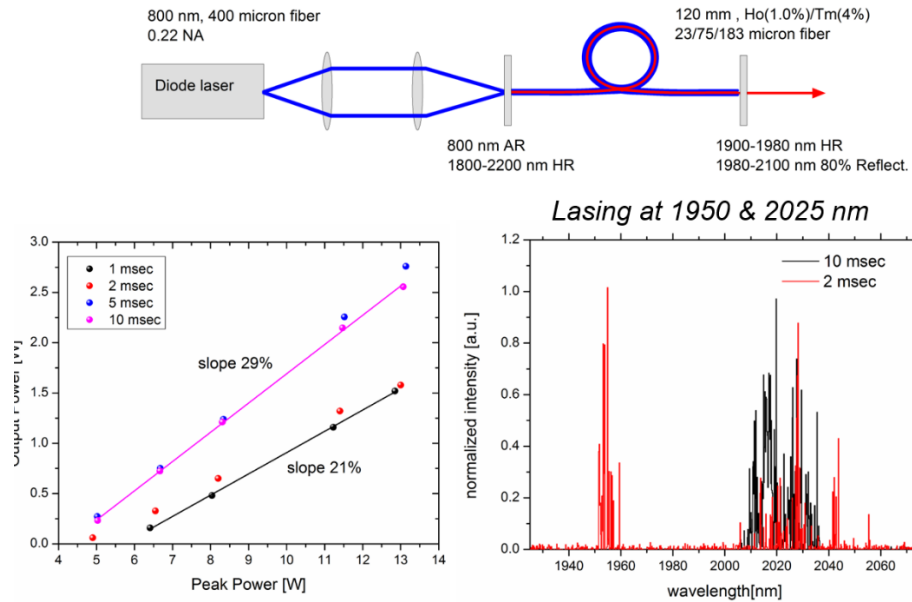


Fig. 9 (Top) Schematic of the 800-nm diode-pumped Tm/Ho composite fiber laser with outcoupler. (Left) Q-CW laser performance of the Tm/Ho composite fiber indicating an overall conversion slope efficiency of 800-nm radiation to 2 micron radiation of 29%. (Right) Spectral output of the laser showing the presence of 1950-nm radiation attributed to leakage of Tm lasing through outcoupler.

In general, it was found that as the length of the fiber was lengthened from 160 to 500 mm, the output wavelength of the fiber lengthened, as well, to 2070 and 2100 nm. Unfortunately, the optical-optical efficiency of the conversion of the 805-nm pump to 2.1- μ m radiation worsened to about 4% for the case of a 300-mm-long fiber, as shown in Fig. 10. Note that the powers are plotted in term of average power at a low duty cycle of 5%.

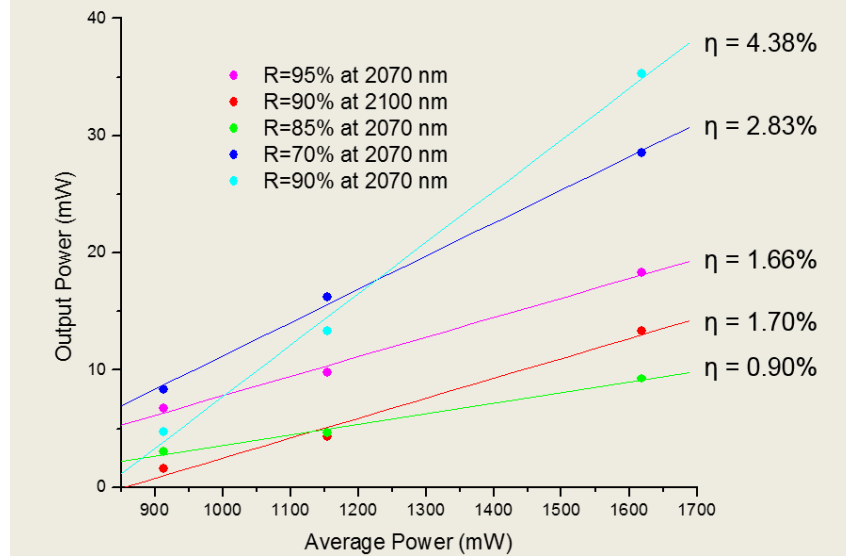


Fig. 10 Laser performance of the 300-mm-long Tm/Ho composite fiber for various output coupler reflectivities

6. Conclusion

I have described the principle and presented the first experimental results of the Tm-doped clad/Ho-doped core fiber laser. In particular, calculations of the model overlap of the cladding modes with the core have been presented in a 1-D waveguide, and by extension, a simple expression for the fraction of mode overlap of the Tm mode with the Ho core. Measurements of the absorption and emission spectroscopy of the Ho and Tm silicate glass have been presented. An expression for the Tm gain cross section of the Tm/Ho composite fiber was proposed to account for the absorption of the Tm radiation by the Ho core to explain the observed emission radiation bands. The slope and power performance of the Tm/Ho composite 2.1- μm fiber laser were presented.

7. References

1. Hemming A, Bennetts S, Simakov N, Davidson A, Haub J, Cater A. High power operation of cladding pumped holmium-doped silica fibre lasers. *Opt. Exp.* 2013;21(4):4560.
2. Moulton PF, Rines GA, Slobodtchikov EV, Wall KF, Frith G, Samson B, Carter ALG. Tm-doped fiber lasers: fundamentals and power scaling. *IEEE J. Sel. Top. Quantum Electron.* 2009;15(1):85–92.
3. Newburgh GA. A composite laser gain medium. United States patent US 9,118,164 Issued August 25, 2015.

List of Symbols, Abbreviations, and Acronyms

1-D	1-dimensional
AR	anti-reflective
ARL	US Army Research Laboratory
E-O	electrical-to-optical
Ho	holmium
HR	highly reflective
NA	numerical aperture
PR	partially reflective
PRF	pulse repetition frequency
Q-CW	quasi-continuous
RIP	refractive index profile
SMLMA	single mode large mode area
TE	transverse electric
Tm	thulium

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